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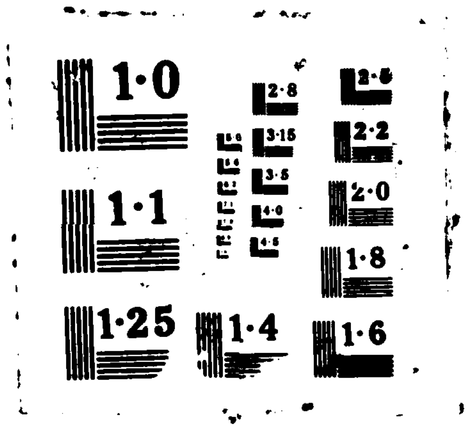
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RADC-TR-86-184
Final Technical Report
December 1986

AD-A178 467

# HIGH CURRENT ELECTRON GUN FOR SPACE FLIGHT

Kimball Physics, Incorporated

G. Dyer

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**ROME AIR DEVELOPMENT CENTER**
**Air Force Systems Command**
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The purpose of this project is to develop a high energy, high current electron gun capable of modulation up to 100 kHz for use in rocket and space shuttle flights. The energy capability ideally should cover the 1 keV to 50 keV range while the current capability should be several tins of amperes.

A module of such an electron gun was constructed on a 4.5 inch Conflat flange. The configuration was as close to the final flight arrangement as possible, keeping in mind the need for flexibility and experimentation. The structure was a triode arrangement with four separate cathodes and control grids. This was changed to a tetrode after early experiments.

Results indicate that this type of approach is ultimately limited by fundamental space charge and current density considerations, rather than by the mechanical difficulties of gun design. At 1 keV beam energy, the maximum beam current density possible within the gun was 0.3 A/sq. cm. Delivery of this beam onto a target of more than 1 cm away proved impossible. (over)


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19. Abstract (continued)

The maximum beam current density possible within the gun is expected to rise to greater than 1 A/sq. cm. when the beam energy is raised to 3 keV, so that the gun would no longer be space charge limited, and could potentially produce 1 A of beam current per cathode disc. As the beam energy is increased the beam will travel farther outlide the gun, particularly in space, where the presence of positive ions will neutralize the electron space charge to a degree.

It appears that by enlarging the beam cross section and by adding collateral beams, the total beam current can be made as large as desired, even with a beam energy as low as 1 keV.

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# SUMMARY

The purpose of this project is to develop a high energy, high current electron gun capable of modulation up to 100 kHz for use in rocket and space shuttle flights. The energy capability ideally should cover the 1 keV to 50 keV range while the current capability should be several tens of amperes.

A module of such an electron gun was constructed on a 4.5 in. Conflat flange. The configuration was as close to the final flight arrangement as possible keeping in mind the need for flexibility and experimentation. The structure was a triode arrangement with four separate cathodes and control grids. This was changed to a tetrode after early experiments.

The problems which were addressed were the space charge problems between cathode and grid and between grid and anode. Thermal and vibrational stability of the gun elements were studied as well as the heat management with regard to insulator failure and feedthrough and connector failure. Lifetimes of all the elements were studied from the point of evaporation loss. Insulation deterioration due to the deposition of evaporants was avoided in the design by suitable shields. Outgassing of elements and the consequent tendency to cause arcovers from locally elevated pressure was also investigated.

The electron gun test module was operated using only one of the 4 cathode discs. At 1 keV beam energy the maximum beam current that could be reached was 450 mA continuous. The beam current at full cutoff was 1 mA. The grid to cathode capacitance including the cable contribution was 175 pF so that modulation at 100 kHz was not expected to be a difficulty.

Focusing of this electron beam in the 1 keV to 5 keV energy range to a narrow angle of 10 degrees or less presents a difficult problem and was not addressed experimentally in the test setup.

Results indicate that this type of approach is ultimately limited by fundamental space charge and current density considerations rather than by the mechanical difficulties of gun design. At 1 keV beam energy the maximum beam current density possible within the gun was 0.3 A/sq. cm. Delivery of this beam onto a target of more than 1 cm away proved impossible.

The maximum beam current density possible within the gun is expected to rise to greater than 1 A/sq.cm when the beam energy is raised to 3 keV, so that the gun would no longer be space charge limited and could potentially produce 1 A of beam current per cathode disc. As the beam energy is increased the beam will travel farther outside the gun, particularly in space where the presence of positive ions will neutralize the electron space charge to a degree.

It appears that by enlarging the beam cross section and by adding collateral beams the total beam current can be made as large as desired, even with a beam energy as low as 1 keV.

# A HIGH-CURRENT ELECTRON GUN FOR SPACE FLIGHT

## THE TECHNICAL PROBLEM

A high-current electron gun producing several amperes of beam current at tens of keV's of beam energy, capable of modulation over a wide dynamic range and sufficiently durable for space use represents a considerable advance over the present state of the art. Present electron guns in space use are limited to approximately a quarter ampere at 40 keV without modulation and with a low duty cycle or to about 20 mA at 3 keV with full modulation over a wide dynamic range and 100% duty cycle.

The principal problems involved in the high-current electron gun are:

1. The development of a cathode which will produce a large current for a reasonable power input, which is not poisoned by exposure to the atmosphere, which has a lifetime adequate for the work involved, and is sufficiently rugged for space flight.

2. The development of a grid matched to the above cathode. A grid is the only means of controlling the electron beam to produce the wide dynamic range of, say, a million in beam current. For a grid and cathode system to produce the high perveance necessary for the required maximum beam current, the grid to cathode spacing must be so small, of the order of 15 mils, that the dimensional stability of both these members, as well as the spacing between them, becomes a difficult engineering problem. The maximum positive potential which may be applied to the grid is that value which causes heating of the grid to an extent that there is significant electron emission from the grid, thus fixing the minimum beam current, for the changes in modulation are normally much faster than the thermal time constant of the grid. The grid-cathode spacing and the maximum positive grid potential essentially determine the perveance of the electron gun.

3. Insulators. All insulators become increasingly conducting as their temperatures are raised. Thus with alumina the temperature limit is about 1300 deg. K for adequate electrical insulation. For higher beam voltages insulation paths must be longer. If these long insulators are also providing mechanical support their strength must be adequate for space flight. Insulators must be shaded from evaporating metal which may compromise them over the long term.

4. Heat management. Metal members can be constructed from refractory metals so that they can usually be adequately cooled by radiating away their heat into space. However the insulators must not be allowed to exceed their maximum working temperature. To this end it may be necessary to conduct a large amount of heat away to the flange with a cooling loop in order to keep insulators adequately cool. Thus it is desirable for a minimum of beam current to be intercepted on the anode.

## TECHNICAL OBJECTIVES OF PHASE 1

1. To design a cathode and grid system with adequate emission, stability, perveance, and ruggedness.

2. To design an electron gun module structure which has adequate heat dissipation to protect the insulators, which has sufficient mechanical strength for the rigors of space flight, and can be stacked close together to form a much larger gun structure of 16 modules in a space of 12 in. x 12 in. x 6 in. thick, or even as many as 100 modules but limited to a light duty cycle.

3. To construct the test module described in objective 1.

4. To test the cathode-grid assembly to see that it meets emission, dynamic range, and insulation breakdown requirements.

5. To shake test the cathode-grid assembly to ensure that it meets rocket flight requirements. This must be done by the Air Force since Kimball Physics does not have a vibration testing facility.

6. To construct the rest of the test module as described in objective 2, including the anode structure, in such a way that individual modules can be disassembled to change cathodes, grids, Wehnelts, or anodes without disturbing neighboring modules in the final gun.

7. To test the complete gun to the limit of existing Kimball Physics' power supplies. The minimum beam energy for full beam current will also be determined.

8. To shake test the complete module to prove flight worthiness. Again this test must be performed by the Air Force as Kimball Physics has no shake test facility.

## THE TEST MODULE

The test module was designed to be as close to final configuration of the ultimate flight module as possible but still be sufficiently versatile as to allow laboratory testing and changing of components and spacings as the test results seemed to warrant.

The test module is shown in Fig. 1. It is a complete electron gun in itself and could be used where the beam current requirement does not exceed 4 A. A schematic is shown in Fig. 2.

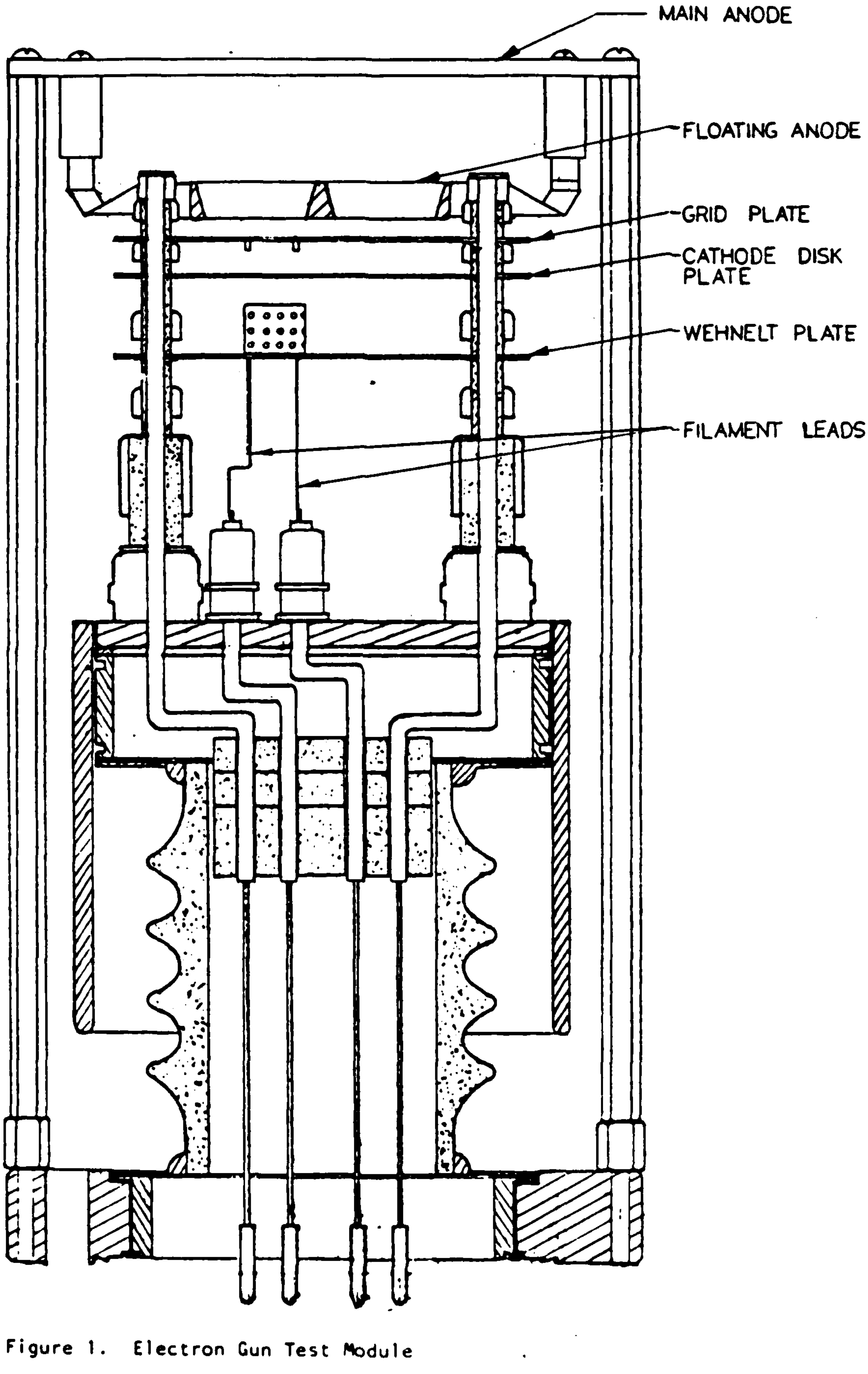



Figure 1. Electron Gun Test Module

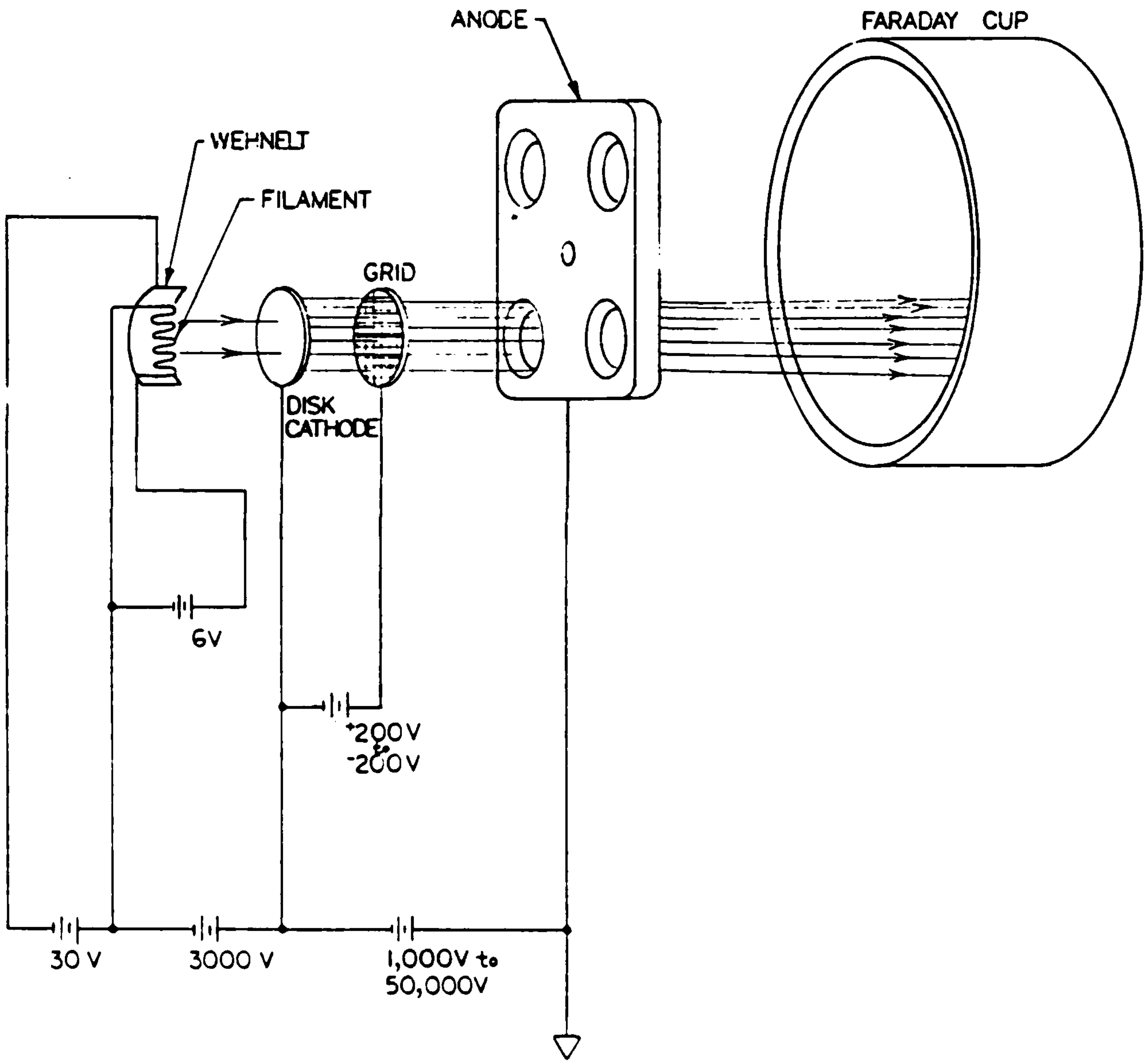



Figure 2. Schematic of Test Module

The test module was constructed on a 4.5 in. Conflat flange with the sealing edge away from the electron gun. This allows the largest possible module to be constructed on a given size flange since the gun would be mounted on the outside of the bulkhead on a satellite or rocket. Thus modules will not have wasted space between them. To enable testing in a laboratory vacuum system an adaptor flange from a 4.5 in. Conflat on one side to an 8 in. Conflat on the other side allows mounting in the usual manner.

In this test module there are four sets of each element, i.e., four filaments, four main cathodes, and four grids. Thus if one filament or cathode or grid fails the module can continue at 75% capacity providing a short has not developed which would prevent the module from operating. It is intended that each set will deliver a one ampere beam of electrons.

The test module was constructed using one large (1.5 in. I.D., 2.5 in. O.D.) 50 kV insulator welded directly to the 4.5 in. flange. At the other end of the 50 kV insulator was welded a feedthrough plate containing 8 6.6 kV feedthroughs and 4 12.6 kV feedthroughs. The Wehnelt (guard), grid, cathode, and floating anode plates were mounted on insulator stacks on rods through three of the large feedthroughs plus two rods brazed into the feedthrough plate itself.

The anode was supported by four pillars screwed to the 4.5 in. Conflat flange.

## THE CONNECTOR

The connector and power cable designed into the test module are believed to be adequate for space flight in their present condition.

The connector was designed to withstand the 50 kV insulation requirement as well as the difficult heat conduction situation. It requires safety wiring and vibration testing.

Since the teflon cylinder of the female connector must be kept below about 300 deg. C to avoid decomposition of the teflon, heat conduction from the hot gun parts must be limited (Fig. 3). This was accomplished by making the rods from the feedthroughs in the male connector very long, about 5 in., by covering the rods with alumina tubing, and by placing three discs of mullite between the teflon and the hot feedthrough plate to act as a heat shield.

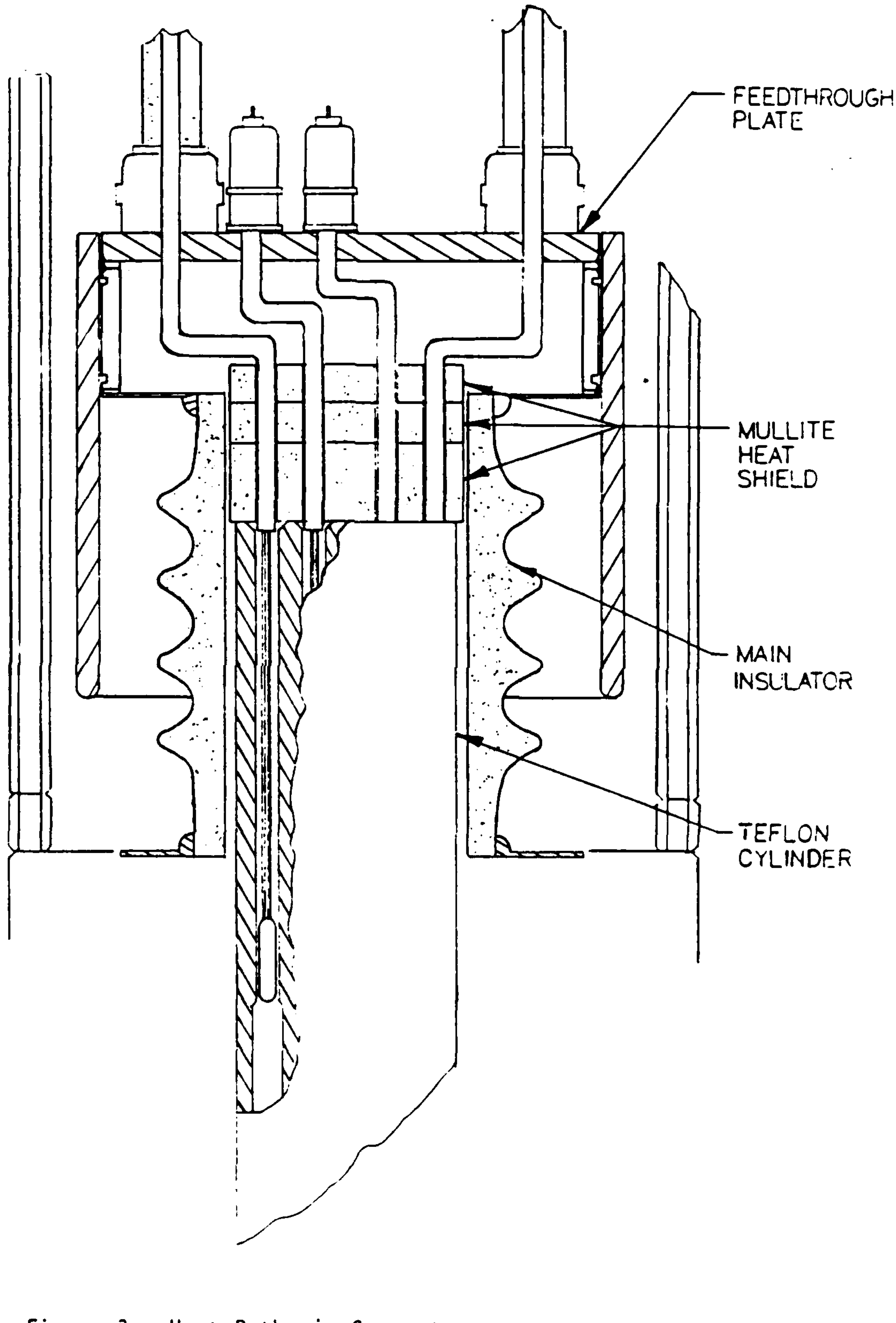



Figure 3. Heat Paths in Connector

## THE FILAMENT

The test module has 4 filaments. Each filament must deliver sufficient bombarding current for the lifetime of the unit, approximately 200 hours. Each filament is a tantalum wire bent into sinusoidal shape (Fig. 4) with a diameter of 15 mils and an effective length of 1 in. Each end of each filament is spotwelded directly to a feedthrough.

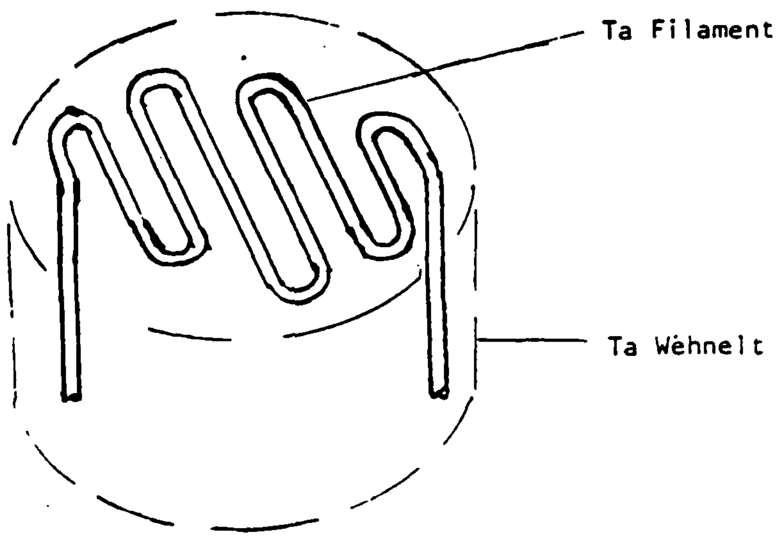



Figure 4. Tantalum Filament for Bootstrap

The bombarding power required to heat each of the 4 disc cathodes is 200 watts. The required emission current is 67 mA at 3 kV bombarding potential. The calculated life time of these filaments is 400 hours.

Each filament has a separate power supply. If a filament burns out the three remaining filaments continue independently, thus preserving 75% of the module beam current.

## THE WEHNELT

To prevent emitted electrons from the filament from striking anything other than their intended target, the disc cathode, an electrode called the Wehnelt, or guard, is placed behind the filament. The Wehnelt consists of a 20-mil tantalum plate with four open tantalum cylinders spotwelded to it. The plate and the cylinders have many holes to allow rapid pump-out of this region (Fig. 5).

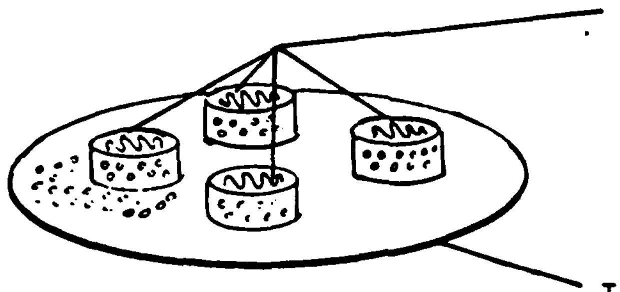


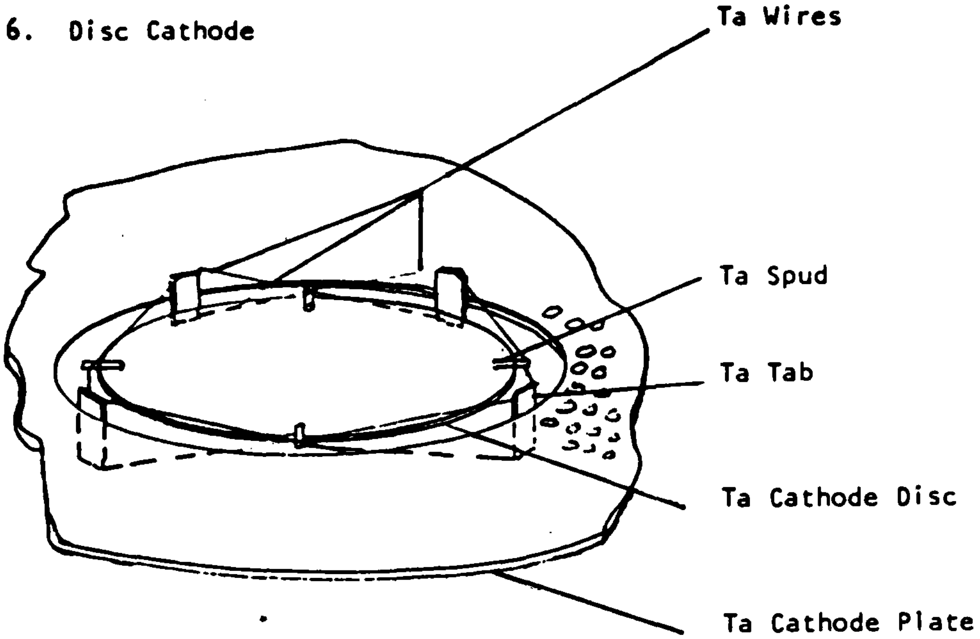

Figure 5. Wehnelt Electrode

## THE DISC CATHODES

There are 4 disc cathodes, each consisting of a 20-mil thick tantalum disc 0.5 in. in diameter. Each disc is supported by 8 4-mil tantalum wires spotwelded in the middle to a spud on the disc, and at the ends to tabs which in turn are spotwelded to the 20-mil thick tantalum support plate (Fig. 6). The spud allows attachment sufficiently away from the edge of the disc to permit the grid to fit closely over the cathode disc. The cathode support plate has 125-mil diameter holes placed so that the web between holes is one tenth of the diameter. The thermal conduction path from the hot cathode discs to the edge of the plate is considerably poorer as a result. The alumina support spacers at the edge of the plate operate considerably cooler, cool enough that there is adequate insulation between cathode and grid. This was not the case without the 125-mil holes.

Bombardment power to each disc should be kept below 300 watts.

Figure 6. Disc Cathode




THE GRID STRUCTURE

Four grids are suspended from the grid plate, one placed about 25 mils above each cathode disc. Each grid consists of 100-mesh, 1-mil, woven tungsten spotwelded to the tantalum frame (Fig. 7). Bootstrap electrons, which are used to bombard the cathode discs to heat them, are confined to a degree by the Wehnelt. However, a few electons miss the cathode disc and go through or by the grid. Since these are 3 kV electrons the grid cannot control them. To prevent these stray bootstrap electrons from getting by the grid, the grid is made the same size as the cathode disc with a curtain placed around the grid. Nevertheless a few electrons manage to get by or through this curtain so that the cutoff current for each grid is about 0.8 mA. This result could be improved undoubtedly by further measures.

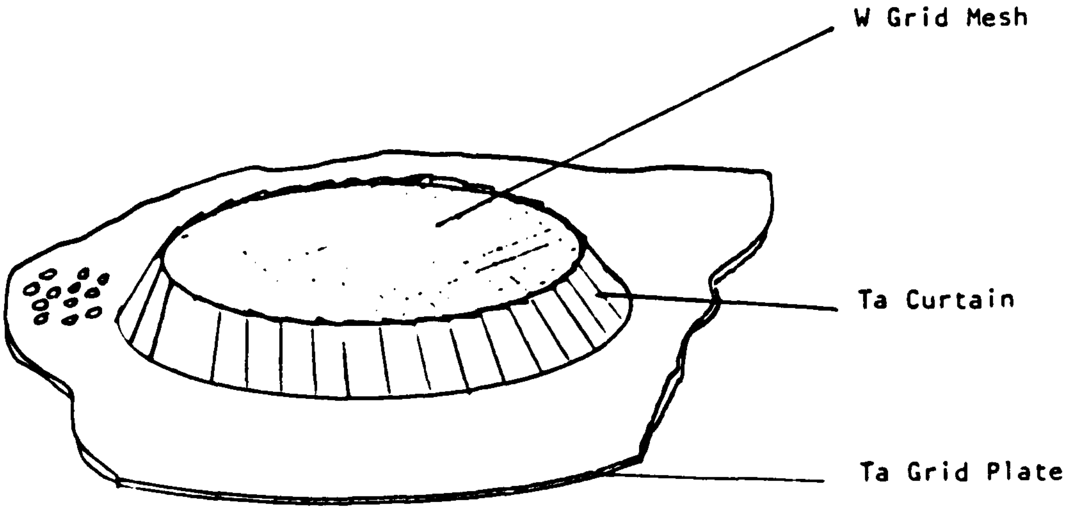



Figure 7. Grid Structure

The grid normally operates between 200 V positive with respect to the cathode disc and 300 V negative. The power dissipation in each of the four grids should be limited to 100 watts.

The grid characteristics (Table III) show that at full beam current there is no space charge limiting of the beam between cathode and grid.

## FLOATING ANODE AND SPACE CHARGE LIMITING

Severe space charge limiting showed up between grid and anode in the first tests.

The anode consisted of a thick stainless steel plate with 4 conical holes (Fig. 9) to match the 4 grid positions. This anode was supported by pillars from the 4.5 in. Conflat flange and was at ground potential.

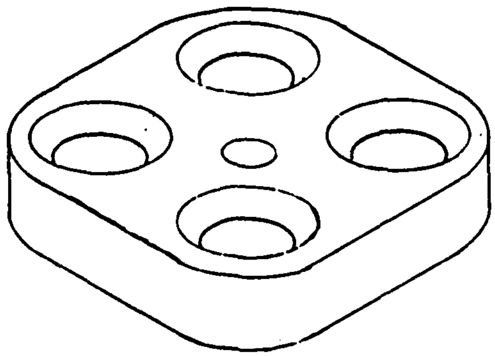


Figure 8. Floating Anode

With the cathode disc (only one disc was used for initial tests) at -1000 V and 0.5 A grid current only 0.25 A beam current could be delivered to the Faraday cup, even when an extension of the cup was placed only 0.3 inch from the anode.

An addition was made to the anode in the form of two strips of tantalum (Fig. 10) placed across one of the 4 anode openings. The object was to increase the field gradient at the center of the anode so that it would be comparable to that near the edge of the hole. This resulted in 0.45 A beam current to the Faraday cup at 1 kV beam energy with a 0.65 A either going directly to the anode or returning to it.

As the high voltage is increased the bombarding power on the two tantalum strips would increase proportionately. It was decided to float this anode at 800 V above the cathode voltage to limit the dissipation on the two tantalum strips. Another, main anode was placed at ground potential.

Due to power supply limitations and limitations of the isolation transformer for the bootstrap energy the maximum beam energy that the module can be tested at is 1200 eV. It appears that the beam current will be much higher, perhaps reaching 1 A at beam energies above 2 keV, when the space charge limitation is removed.

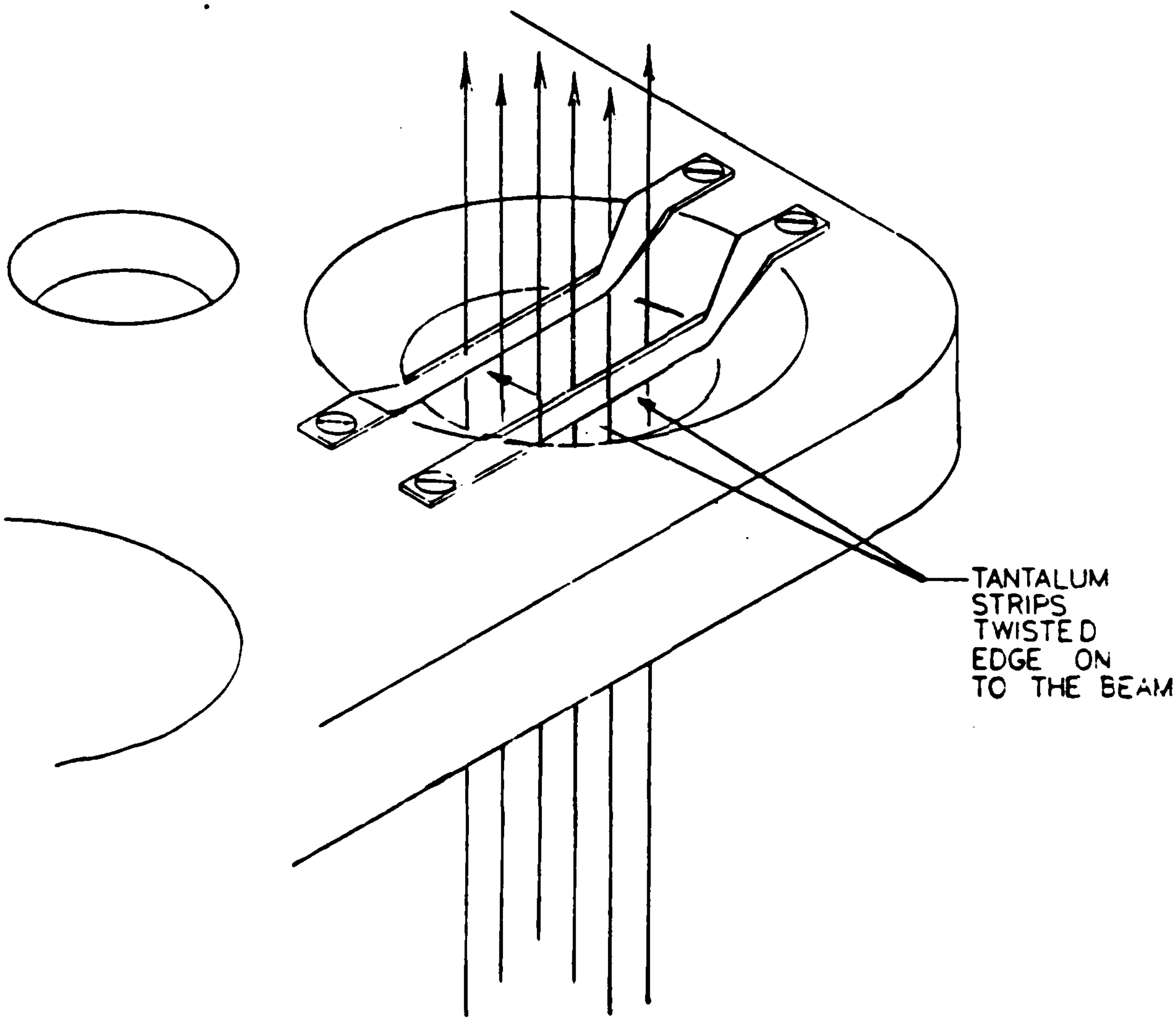



Figure 9. Floating Anode Strips for Improved Field

It is difficult to separate effects due to space charge limiting within the gun compared to space charge limiting between the main anode and Faraday cup. If the floating anode shows a relatively small intercepted current but the main anode current is large compared to the Faraday cup current, this is an indication of a space charge cloud between the anode and the Faraday cup. If the floating anode current is high then there is space charge limiting between it and the main anode. If the grid currrent is high there is a space charge limiting between it and the floating anode. Proportions which show relatively little space charge limiting would be that the grid current is 40% of the Faraday cup current and the floating anode and the main anode currents are each about 20% Of the Faraday cup current.

## THE MAIN ANODE

The main anode in this gun consisted of a metal ring as shown in Fig. 11. The design was not optimized for beam forming or for minimum emission of x-rays at high beam energies. The suggested form of the main anode is shown in Fig. 12. The suggested material for minimum x-rays is beryllium. Otherwise tantalum would be a good choice.

## THE FARADAY CUP

The Faraday cup used in these experiments was water cooled and has a design beam dump capability of 10 kW (Fig. 13).

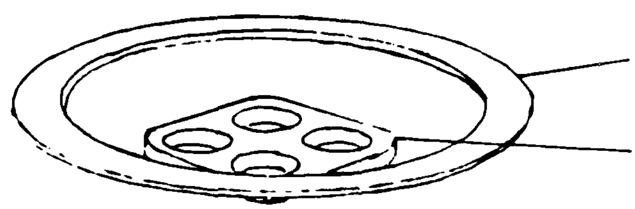



Figure 10. Main Anode on Present Module

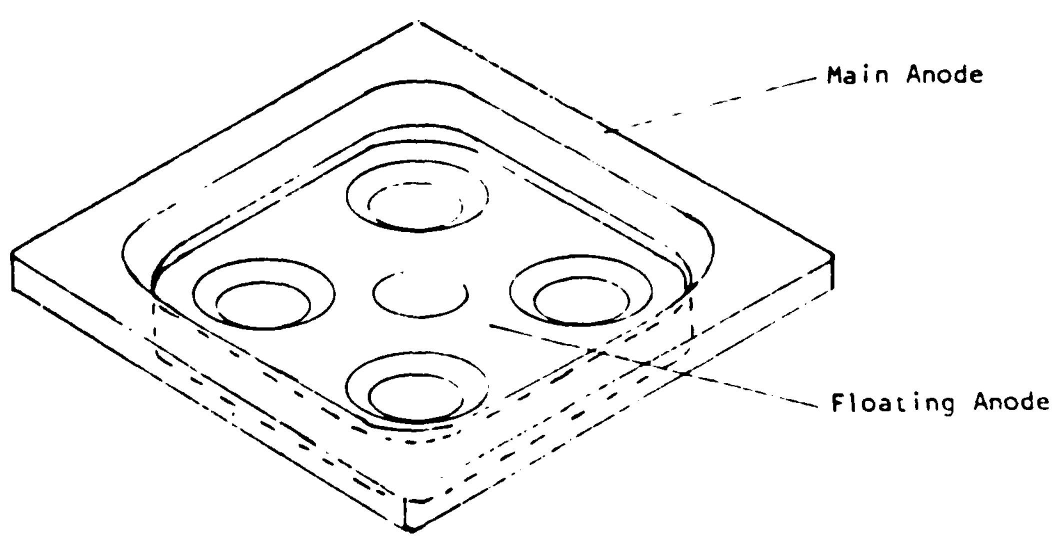



Figure 11. Suggested form of Main Anode

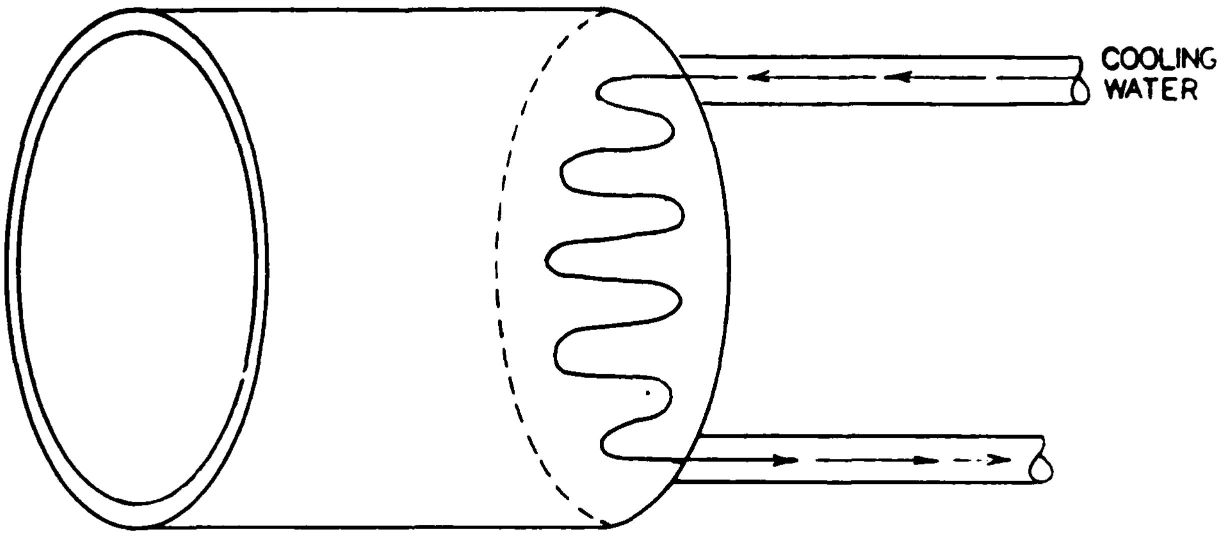



Figure 12. Faraday Cup

## THE INSULATORS

The breakdown potentials of the following insulators were tested in air (Table I). The results in vacuum should be better. In the poor vacuum conditions surrounding the satellite or rocket together with the outgassing effects of the gun itself they may not be much better.

Table I

| Insulator | Breakdown Potential |
|---|---|
| Disc Cathode to Main Anode | 22 kV |
| Disc Cathode to Grid | >0.6 kV |
| Disc Cathode to Filament | 7 kV |
| Grid to Floating Anode | 3 kV |
| Filament to Wehnelt | 5 kV |
| Floating Anode to Main Anode | 7 kV |

In addition to breakdown considerations there are temperature effects on the resistance of insulators. With one quarter of the test module operating at full heat production the disc cathode to grid resistance was above a megohm.

## VIBRATION TESTING

The completed test module has yet to be vibration tested.

Results of a preliminary test of the grid and disc cathode structures carried out at the AFGL vibration facility on 14 November, 1985, showed that these structures would probably pass Shuttle requirements and possibly rocket requirements. Since these are believed to be the weakest structures the expectation is that the test module will pass or can be made to pass at least the Shuttle requirements.

## TYPICAL OPERATION

When it was realized that funds would be exhausted before thorough testing of the module could be completed it was decided to complete the fabrication of the module and concentrate on extreme tests rather than to run characteristic curves. Table II data illustrates maximum beam current conditions:

Table II

Date 05-26-86

| Electrode | No. in use | Potential | Current |
|---|---|---|---|
| Filament | 1 | 6.3 V across | 8.0 A through |
| Bootstrap | * | 1800 v between filament and disc cathode | 0.16 A |
| Wehnelt | * | -30 V relative to filament | 0.000 A |
| Disc Cathode | 1 | -1000 V relative to ground | 1.34 A emission |
| Grid | 1 | +200 V relative to disc cath. | 0.34 A |
| Floating Anode | 1 | -23 V relative to ground | 0.38 A |
| Main Anode | * | Ground | 0.17 A |
| Faraday Cup | * | Ground | 0.45 A |

*Note that there is only one bootstrap circuit, one Wehnelt circuit, one main anode, and one Faraday cup in the test module setup.

Table III data gives some idea of grid characteristics:

Table III

Date 05-15-86

| Electrode | No. in use | Potential | Current |
|---|---|---|---|
| Filament | 1 | 6.5 V across | 8.0 A |
| Bootstrap | * | 1400 V between filament and disc cathode | 0.175 A |
| Wehnelt | * | -20 V relative to filament | 0.000 A |
| Disc Cathode | 1 | -1000 V relative to ground | varies |
| Grid | 1 | + relative to disc cathode varies | varies |
| Floating Anode | 1 | Ground (not floating) | varies |
| Main Anode | * | Not used | |

| Disc Cathode Current (A) | Grid Potential (V) | Grid Current (A) | Anode Current (A) | Faraday Cup Current (A) |
|---|---|---|---|---|
| 0.650 | 160 | 0.150 | 0.17 | 0.330 |
| 0.585 | 130 | 0.135 | 0.16 | 0.292 |
| 0.430 | 100 | 0.105 | 0.09 | 0.234 |
| 0.195 | 50 | 0.045 | 0.04 | 0.107 |
| 0.015 | 0 | 0.005 | 0.00 | 0.007 |

## BEAM CURRENT STABILIZATION

It was found that the beam current would drift around by 10%-20% within a few minutes when the voltage across the filament was held constant to 0.1% with a regulated power supply. Regulating the filament current to the same degree would have even poorer prospects for stabilizing the beam current.

The best approach seemed to be to stabilize the bootstrap power of the bombarding electrons which heat the cathode disc. This can be done by monitoring the emission current from each filament. A feedback circuit to the filament heating voltage maintains this emission current constant. The bootstrap voltage is fixed and regulated and is the same for all 4 disc cathodes since one bootstrap power supply delivers all the current. Such a feedback circuit was built (Fig. 14) but has not been tried yet.

## MODULATION

The capacitance between grids and cathode discs including that contributed by the cable was kept to 175 pF during construction. It should be possible to modulate the electron beam to above 100 kHz without great difficulty.

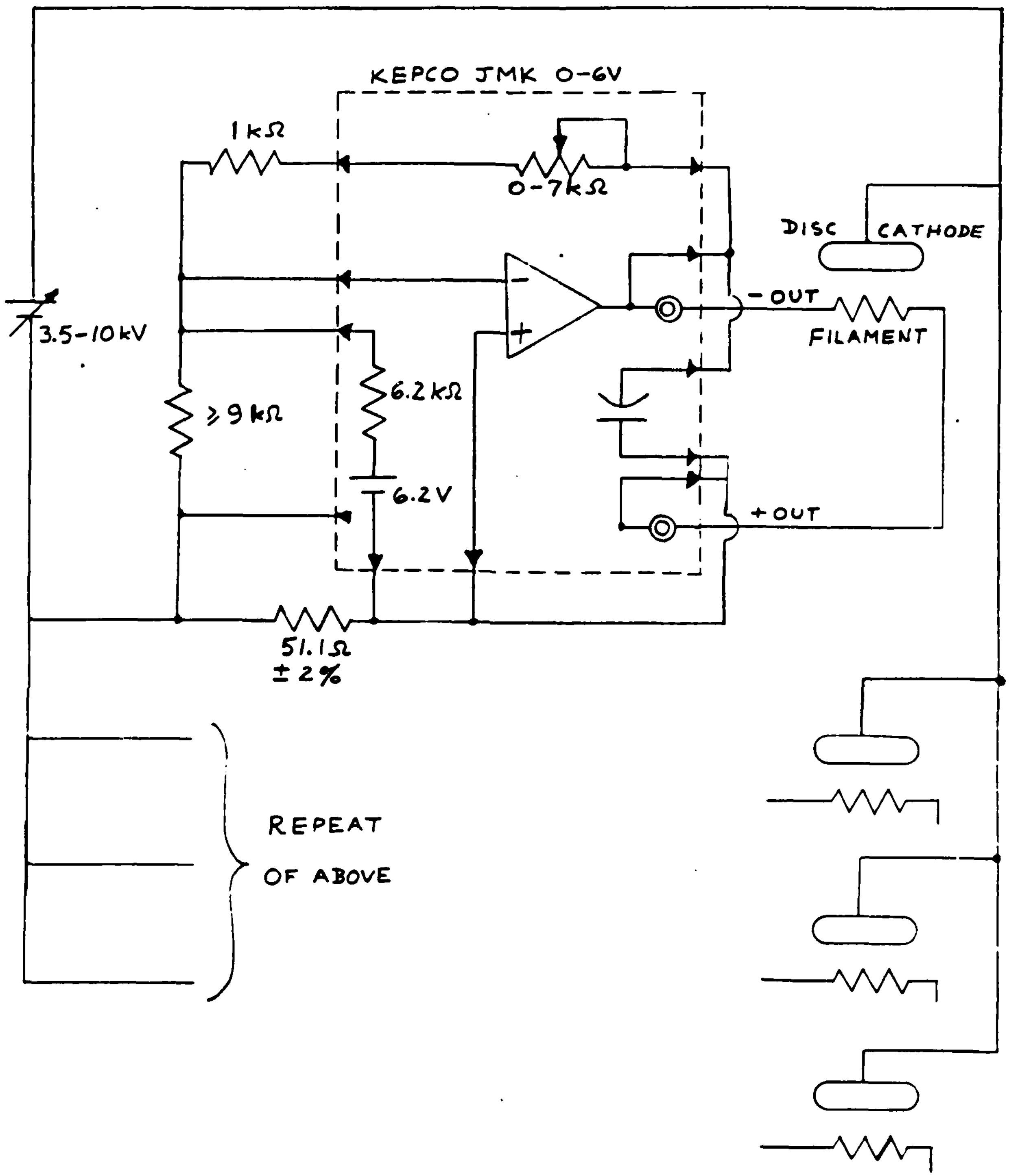



Figure 13. Beam Current Feedback Stabilization Circuit

A circuit was built to square wave modulate using two floating power supplies and switching diodes. The potential applied to the grids (relative to the cathode discs) would be switched between the power supplies for varying on and off times using light diodes, a light pipe, and a signal generator at ground. The circuit is shown in Fig. 15. It has not been tried yet.

## FOCUSING TO NARROW BEAM

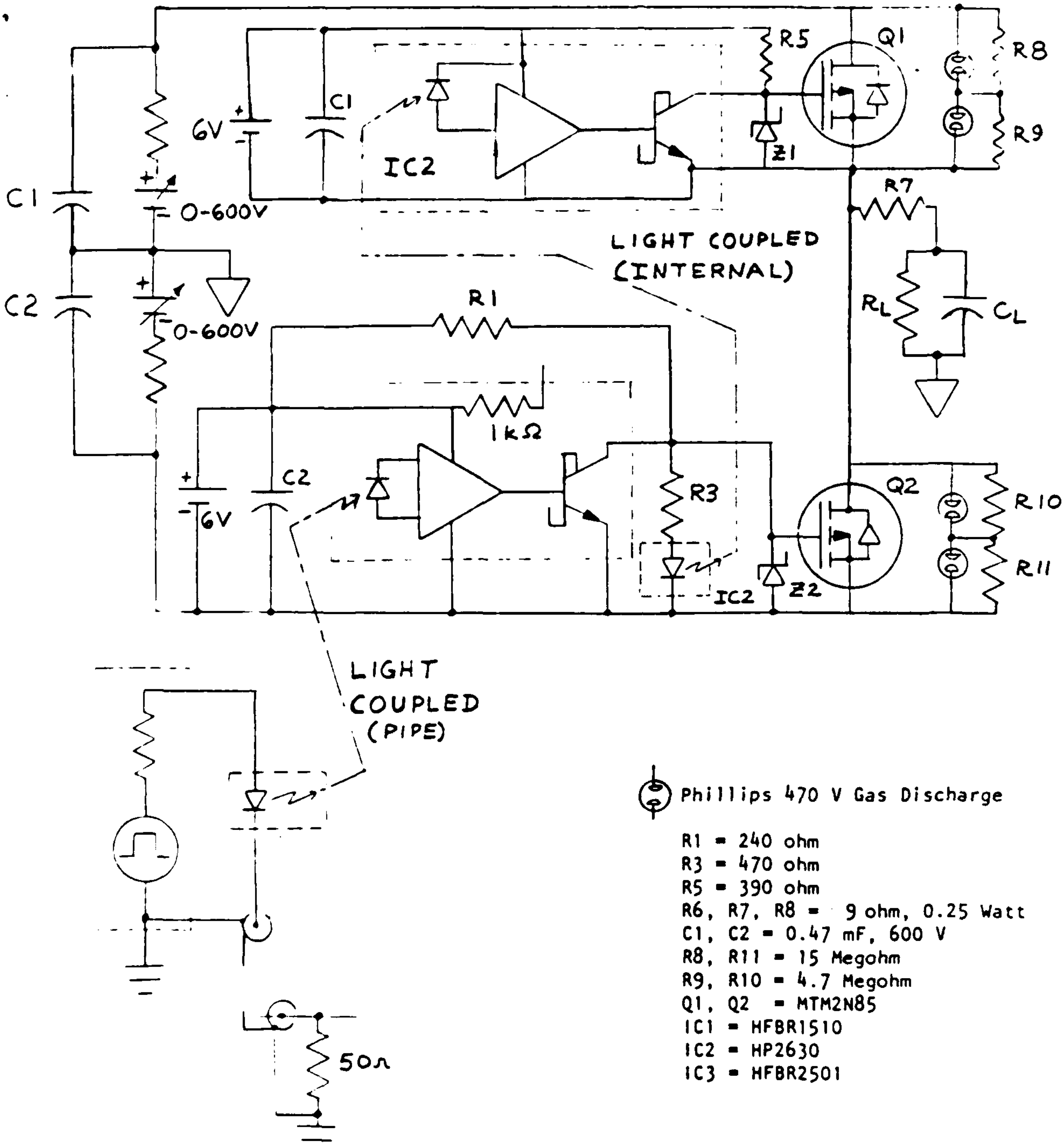
Originally it was planned to try to focus the beam to a 5 deg. FWHM or smaller. There are several difficulties involved.

Producing a small image angle requires a small object angle to start with, which means either a small object or a long focal length for the lens, either electrostatic or magnetic. However the object (the 4 cathode discs) is 1.5 in. in diameter so that the lens center would have to be about 17 in. away with at least a 6 in. diam. bore to hope to focus the beam to 5 deg. This assumes there are no space charge limiting situations. In fact there appears to be a significant space charge limiting problem below 3 keV beam energy. To solve the space charge problem requires a lower current density, i.e. a larger cathode disc area, hence a larger object, and a longer lens focal length for the same FWHM angle. Thus focusing is probably not practicable below 5 keV with beam currents of several 10's of amperes as was originally intended.

## SUGGESTED EXPERIMENTS AND IMPROVEMENTS

A much larger proportion of the effort of this contract went into hardware fabrication than into testing and experimentation. Consequently a number of experiments and improvements suggest themselves immediately:

1. The full cut-off current should be reduced by making a better grid curtain which does not allow electrons through, or by having no 0.125 in. diameter holes in the grid plate where there is presently a row right next to the curtain.
2. Operate the test module with all 4 filaments and all 4 cathode discs at temperature to see the effect on a.) the connector teflon cylinder temperature, b.) the insulation between cathode discs and grids, c.) the floating anode temperature, d.) the space charge situation and the deliverable beam currrent. Determine how many of the 4 sets can be operated continuously if it is less than 4.
3. Operate the test module at higher beam energies to ensure that the space charge problem goes away as predicted.
4. Measure the beam FWHM angle at various distances and energies.
5. Stabilize the beam current (actually the cathode disc temperature) with the circuit provided.
6. Modulate the beam current with the circuitry provided.




Phillips 470 V Gas Discharge

R1 = 240 ohm
R3 = 470 ohm
R5 = 390 ohm
R6, R7, R8 = 9 ohm, 0.25 Watt
C1, C2 = 0.47 mF, 600 V
R8, R11 = 15 Megohm
R9, R10 = 4.7 Megohm
Q1, Q2 = MTM2N85
IC1 = HFBR1510
IC2 = HP2630
IC3 = HFBR2501

Figure 14. Modulation Curcuit

8. Determine the duty cycle possible at higher beam energies where the main anode may melt. Change the anode material to tantalum or beryllium if melting occurs or excesssive x-rays apppear.

9. Determine the maximum beam current possible with a short (1 microsec.) pulse which could be much higher than the maximum possible steady state current.

10. Make the floating anode of lighter construction to put less stress on the supports during vibration testing.

11. Vibration test (after safety wiring) to show up weaknesses in the design.

12. Determine how quickly the bootstrap current can be brought up to full value at 4 kV bootstrap potential without producing a discharge from rapid outgassing.

13. Check for nitrogen embrittlement of the 4-mil tantalum cathode disc support wires. It may be necessary to use 5-mil rhenium support wires.

## CONCLUSION

The test module delivered under this contract has demonstrated that it can be the basis for an electron gun for space use which can be modulated at up to 100 kHz delivering 10's of amperes at 1 keV to 50 keV. Ten such modules should constitute such an electron gun.

More testing and evaluation of the delivered test module is necessary to find its limitations and to suggest design changes where necessary or desirable.

## CONTRIBUTORS

The following people made significant contributions to this research project:

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Mr. John J. Watt
Mr. Thomas S. Tyrie
Dr. Charles K. Crawford

# MISSION
## of
## Rome Air Development Center

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